Case Study on Sustainability Criteria for Plastics Design, from a Chemicals Perspective: Insulation
Healthy Building Network

Introduction

Purpose of case study

Plastic production has increased exponentially over the last 65 years, reaching 448 million tons in 2015 (Parker, 2019). Half of all plastics on earth today were made in the last 15 years (Parker, 2019). Behind packaging, the building and construction industry is the second largest consumer of plastics, comprising 16% of global plastic production (Barron, 2016; Parker, 2019).

The goal of this case study is to build on the findings from the recent OECD report "Considerations and Criteria for Sustainable Plastics from a Chemical Perspective" (OECD, 2018) and explore the human health and environmental impacts of chemicals in plastic materials in the building and construction sector using insulation as an example. By evaluating selected plastic insulation products, we explore how the selection of base plastics and associated chemical additives impacts the material life cycle with an eye to designing and managing materials, products, and processes for safety and sustainability, consistent with the OECD Policy Principles for Sustainable Materials Management (Text box 1). Our research focuses on opportunities to reduce exposures to hazardous chemicals for fenceline communities, building occupants, and workers in manufacturing, installation, recycling, and disposal. For the purpose of this case study we define hazardous chemicals as Substances of Very High Concern for REACH (SVHC) or those on the ChemSec Substitute it Now List (SIN) unless otherwise noted (ChemSec, n.d.; ECHA, n.d.).

Text box 1: OECD Policy Principles for Sustainable Materials Management (OECD, 2010):

1. Preserve natural capital
2. Design and manage materials, products, and processes for safety and sustainability from a life-cycle perspective
3. Use the full diversity of policy instruments to stimulate and reinforce sustainable economic, environmental, and social outcomes
4. Engage all parts of society to take active, ethically-based responsibility for achieving sustainable outcomes

This case study will not address all elements critical to sustainable production, which include cost, performance, availability, consideration of non-plastic alternatives, and social and environmental justice. Nor does it include full life-cycle analysis or a full review of regulatory restrictions. These are important topics and should be considered during materials selection.

Insulation Landscape

Insulation comes in various forms, including batts or blankets, rigid boards, loose fill, and spray foam insulation. It is made from a variety of materials including glass fiber, mineral wool, cork, cellulose, foamed plastic, and wood fibers. These materials offer a wide range of thermal conductivities for any given thickness. In the US, plastic foam insulation accounts for nearly half of the insulation sold (Energy Efficiency for All, 2019).

The global insulation market is growing and is predicted to reach $80 billion USD (about 68 billion euros) by 2026 (Global Market Insights, Inc, 2019). Increased use of insulation has been driven by increased demands for residential and commercial construction, as well as increased energy costs and regulations related to energy conservation (Global Market Insights, Inc, 2019; ReportLinker, 2016). Plastic foam insulation is projected to grow the most rapidly due to its low thermal conductivity (high R-value per inch) (ReportLinker, 2016).

While plastic foam insulation is typically designed to last around 60-75 years, energy-efficiency retrofits are also introducing new materials into existing buildings (EPS Industry Alliance, 2017; Owens Corning, 2019; PIMA, 2015; SPFA, 2018). Since insulation is rarely replaced in a building, hazardous chemicals can have an impact on building occupants for decades.

Design Requirements for Insulation

The primary job of insulation materials is to reduce the transfer of heat from inside a building to outside, and vice versa. The insulative properties, conveyed as R-values or thermal conductivity, are paramount. In some cases, such as retrofit applications, there may be limitations to the thickness of material that can be used, so the insulative performance per inch of material can also be important. Insulation may be required to meet certain flammability requirements, and it may be desirable for the insulation to have vapor retarder or air barrier properties for certain applications. Additional design requirements that are beneficial from a sustainability and circularity perspective are the use of chemicals that eliminate or minimize hazards and pollution throughout the product's life, incorporation of recycled content, and design for reuse and recyclability.

Product Types Selected for Case Study

This case study will consider four types of plastic insulation:

1. Expanded polystyrene (EPS),
2. Extruded polystyrene (XPS),
3. Polyisocyanurate (polyiso), and
4. Spray polyurethane foam (SPF).

These insulation materials are commonly used and represent different polymer chemistries, different additive concerns, and a range of exposure considerations at different stages of the product life cycle. SPF can be either open cell or closed cell. Open cell and closed cell SPF are similar in composition, but use different blowing agents and have different finished product characteristics. In some cases, differences between these two types of SPF are also noted.

The polymer itself accounts for about 75-95% of the total weight of a plastic insulation product. Common additives include blowing agents to create the foam structure and influence insulative properties, and flame retardants to meet flammability standards. Blowing agents off-gas to different degrees during manufacturing, but make up about 2-9% of the product as delivered to the job site. Flame retardants typically make up about 1-6% of the weight of the product, but may account for up to 20% in some products, particularly open cell spray foam insulation (Icynene, 2017, 2019). Other additives that are used in some of the product types include process aids, stabilizers, and facing materials. Some foam insulation also contains recycled content. Product content and process chemistry information provided throughout this case study is based on Common Product research unless otherwise noted. Details on the typical chemical content, the functional roles of that content, and percentage in the product is provided in Appendix A for each insulation type. This same product information and original source documentation is also available in the Common Products section of the Pharos database (Healthy Building Network, n.d.).

The product types selected have a range of thermal conductivities/R-values. EPS and open cell SPF have the highest thermal conductivity (lower R-value per inch) of the plastic foam insulation. XPS has intermediate thermal conductivity, and polyiso and closed cell SPF report the lowest thermal conductivity (highest R-value per inch) of these products (Energy Efficiency for All, 2018). The methods of manufacture and chemicals used influence the relative insulation performance between products.

Chemical Considerations Throughout the Life Cycle

Plastic insulation products can have human and environmental health impacts at every stage of the product life cycle, including production, installation, use, and disposal or recycling. Different plastics use different feedstocks, monomers, and catalysts and require different functional additives. The type of polymer and additives can impact the recyclability or releases at end of life. This section of the case study outlines some of these differences.

Production & Manufacturing

Base Polymer Source Materials

Two primary polymer chemistries are used in foam insulation. These are polystyrene, used in EPS and XPS insulation, and polyurethane/polyisocyanurate, used to make SPF and polyiso. Both polyurethane and polyisocyanurate are based on a reaction of isocyanates and polyols and use similar process chemistry, therefore they are combined in this section for simplicity. Table 1 summarizes the chemical inputs and possible exposure scenarios for the base polymer materials. Ideally, in any comparison of polymeric materials, the process chemicals for additives would also be considered, but that is outside the scope of this review.

Table 1. Chemicals used to make base polymer source materials. **Chemicals that are in red and bolded are identified as Substances of Very High Concern (SVHC) for REACH**, either banned unless authorized, candidate list, or prioritized for listing. Chemicals in red and underlined are on the SIN list.

	Polystyrene (used to make EPS and XPS)	Polyurethane/Polyisocyanurate (used to make SPF and polyiso)
Chemical Inputs		
Primary Chemicals	Ethylene Benzene	Isocyanate: Benzene Ammonia Hydrogen Methanol Carbon Monoxide Sodium Hydroxide

		Chlorine
Intermediates	Ethylbenzene	Isocyanate: Nitric Acid **Nitrobenzene** Aniline Formaldehyde Phosgene **MDA**
Monomers	Styrene	Isocyanate: MDI Polyol:* Ethylene oxide Formaldehyde **1,2-propylene oxide**
Catalysts/process chemicals for different stages	Zeolites Aluminum chloride	Mercury Asbestos **PFAS diaphragm or membrane^**
Potential Exposure Scenarios	Occupational Human and environment via environmental releases during manufacture	Occupational Human and environment via environmental releases during manufacture

*A wide range of chemicals can be used to produce polyols. Because of the wide range of possibilities, this table highlights the three SVHC or SIN list chemicals associated with the polyols that were identified in HBN's Common Product Research as example process chemicals.
^Some chemicals within the PFAS class are known to be hazardous and are considered SVHCs
Sources for table: (Franklin Associates, 2011; Healthy Building Network, n.d.; Lithner, 2011; National Center for Biotechnology Information, n.d.; Rossi and Blake, 2014)

Polystyrene (used to make EPS and XPS)
The production of polystyrene is based on a standard chemistry with minimal opportunities to substitute or vary the materials used. Benzene, a primary chemical input, and the monomer styrene are on the SIN List. The production of the polymer takes place separately from the manufacturing of the insulation product.

Polyurethane/Polyisocyanurate (used to make SPF and polyiso)
Polyurethane/polyisocyanurate chemistry has many steps involving many chemicals and some opportunities to make different chemical choices. The primary chemicals that react to make the polymer are a pre-polymer material called a polyol and an isocyanate or polyisocyanate. Isocyanate manufacturing starts with chlorine. Production of chlorine gas relies on one of four different technologies. Older technologies utilize mercury cells and asbestos diaphragms. Newer technologies either use per- and

polyfluoroalkyl substance (PFAS) diaphragms or PFAS-coated membranes. All four methods of production are still widespread. (Vallette, 2018, 2019). All of these technologies rely on hazardous chemicals, with mercury and asbestos being on the SIN list and some of the chemicals in the PFAS class identified as SVHCs, with many more PFAS chemicals unstudied for health impacts. The commonly used isocyanate is diphenylmethane diisocyanate (MDI). MDI uses additional chemicals of concern in the manufacturing process, including SVHCs nitrobenzene and 4,4'-methylenedianiline (MDA).

Polyisocyanurate commonly uses a polyester polyol which can have various inputs, but may use ethylene oxide, a SIN List chemical, in the manufacture of a monomer used. Polyurethanes in spray polyurethane foam insulation typically contain multiple types of polyols which can vary widely in their monomers, but may include SVHCs and SIN List chemicals, including formaldehyde and 1,2-propylene oxide. Polyols may also have some bio-based content ("Polylabs to present innovative, biobased lightweight spray foam at upcoming PSE," 2017).

Neither polystyrene or polyurethane/polyisocyanurate entirely avoid hazardous chemicals in the base polymer source materials. However, polystyrene manufacturing does not appear to require the use of SVHCs, whereas several SVHCs are common in the supply chain to manufacture polyurethane and polyisocyanurate.

Product Manufacture

Plastic insulation manufacturing processes vary between product types. EPS manufacturers typically receive a pre-made resin consisting of beads of polystyrene and additives, which they then expand and mold into a board (EPS Industry Alliance, 2017). XPS manufacturers receive polystyrene granules and incorporate additives as part of the product manufacturing (Owens Corning, 2019). Polyiso manufacturing involves reacting the raw materials to generate the polymer as part of the product manufacturing (PIMA, 2015). SPF insulation is reacted on site when it is installed in a building, and thus may arguably be considered to be manufactured at that stage. For this analysis, SPF manufacturing will be considered as the actions performed in a factory setting to prepare the components for sale, primarily blending of the ingredients into A-side and B-side components (SPFA, 2018). We also consider the product manufacture stage to include manufacturing of formulated pellets that are later used for insulation manufacturing, as is the case for EPS. Table 2 summarizes some of the primary differences between the product types being considered and likely exposure scenarios during product manufacturing.

Table 2. Chemicals used during product manufacture. **Chemicals that are in red and bolded are identified as Substances of Very High Concern (SVHC) for REACH.** Chemicals in red and underlined are on the SIN list. *Substances in italics are chemicals identified by HBN as a high priority to avoid in insulation* that are not already highlighted in the SVHC or SIN list.

	EPS	XPS	Polyiso	SPF
Flame Retardant	**Hexabromocyclo dodecane (HBCD)** Or	**HBCD** Or *Benzene, ethenyl-, polymer with 1,3-*	Tris(2-chloroisopropyl) phosphate (TCPP)	TCPP

	Benzene, ethenyl-, polymer with 1,3-butadiene, brominated	*butadiene, brominated*	Or Reactive non-halogen: diethyl hydroxymethyl phosphonate	
Blowing Agent	Pentane Cyclopentane Isopentane	*HFC-134a* Or *HFO-1234ze* Or CO_2 and hydrocarbons such as isobutane	Pentane Occasional: 1-bromopropane	*HFC-245fa* (closed cell SPF) Water (open cell SPF)
Catalysts	N/A	N/A	Potassium 2-ethylhexanoate Potassium acetate 1,2-Ethanediamine, N1-(2-(dimethylamino)ethyl)-N1,N2,N2-trimethyl-	Dibutyltin dilaurate Various amine catalysts
Reactive Monomers	N/A	N/A	*MDI*	*MDI*
Potential Residual Monomer	Styrene	Styrene	N/A	Formaldehyde
Optional Additives	Insecticide: such as Disodium octaborate tetrahydrate	N/A	N/A	N/A
Recycled content	Pre-consumer Recycled EPS	Pre-consumer Recycled EPS Post-consumer polystyrene	N/A	N/A
Potential Exposure Scenarios	Occupational Human and environment via	Occupational Human and environment via	Occupational Human and environment via	Occupational Human and environment via

	environmental releases during manufacture	environmental releases during manufacture	environmental releases during manufacture	environmental releases during manufacture

Sources for table: (BASF SE, 2017; EXIBA, 2019; Healthy Building Network, n.d.; SPFA, 2018)

Flame retardants

Flame retardants and blowing agents are used in almost all plastic insulation. Commonly used flame retardants, such as hexabromocyclododecane (HBCD) and tris(2-chloroisopropyl) phosphate (TCPP), are SVHCs or are on the SIN List. Exposures to workers and releases to the environment are possible in the manufacturing stage. The polymeric flame retardant is considered less hazardous so may be less of an exposure concern during insulation manufacturing, though there may be concerns about occupational exposures when the flame retardant is manufactured (Charbonnet, Weber and Blum, 2020; USEPA, 2014). If polymeric flame retardants contain low molecular weight oligomers or impurities, these could be hazardous and present a greater concern (USEPA, 2014). This should be considered for the specific polymeric flame retardants used. In addition, under certain conditions the polymeric, brominated flame retardant may break down into hazardous chemicals in the environment if releases during manufacturing occur (Koch et al., 2019). Halogenated flame retardants in general are considered a high priority to avoid in insulation by HBN because of life cycle concerns. Halogen-free polyiso products are currently available in some regions (Buhrman, 2017; GAF, 2017). The flame retardant reacts during manufacturing to become part of the polymer. The specific chemical used in products is not publicly disclosed, but patent information suggests it may be diethyl hydroxymethyl phosphonate, which is not an SVHC or on the SIN list (Nandi, Wang and Asrar, 2015). See the Use as Installed section below for more details on the flame retardants used in the different product types.

Blowing agents

Blowing agents vary between and within product types. While not common, polyiso may include 1-bromopropane, which is on the SIN List, as a blowing agent. XPS and closed-cell SPF commonly use halogenated blowing agents such as hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs). Some regions may still use hydrochlorofluorocarbons (HCFCs). These blowing agents do not have health impact concerns during the product manufacturing, but are identified by HBN as a high priority to avoid in insulation because of high global warming potential (GWP) of the blowing agent itself, or of chemicals used in the manufacturing process (Healthy Building Network, n.d., n.d., n.d.). Non-halogenated alternatives are commonly used in XPS in Europe (BASF SE, 2017; EXIBA, 2019). These blowing agents do not have high GWP or use high-GWP chemicals in their manufacture, but do lead to a lower insulative performance for the product (Energy Efficiency for All, 2018; EXIBA, 2019; JACKON Insulation GmbH, 2015). Product innovation can lead to improved performance for products with non-halogenated blowing agents. For example, a modified EPS material known as graphite polystyrene (GPS), includes graphite as an additive, which changes the reflection and absorption behavior to improve insulation performance (Atlas EPS, 2018). This improves thermal resistance by 17-50% over standard EPS for different classifications of EPS (Atlas EPS, 2018; EPS Industry Alliance, 2017).

Other additives

Catalysts are required for polymerization for polyiso and SPF. SPF commonly uses organotin compounds such as dibutyltin dilaurate, which is on the SIN List.

Residual monomers may be present in the already made polymers and polyols. The bigger hazard concern at this stage is potential exposure to reactive monomers. Isocyanates such as MDI have been identified by HBN as a high priority to avoid in insulation as respiratory sensitizers. Manufacturing facilities may be able to use closed systems and ventilation to reduce the potential for exposure (NIOSH, 2014).

Insecticides may be included in some EPS products for specific applications in regions where termite infestation is "very heavy" according to building code. These insecticides can be hazardous.

Manufacturing processes can impact additional additives that may be required. For example, the brominated polymeric flame retardant used in XPS insulation requires stabilizers due to the high processing temperature. Common stabilizers are not SVHCs or on the SIN List.

Recycled content

Polyiso and SPF insulations do not typically contain recycled content (PIMA, 2015; SPFA, 2018). Some polyiso products may have paper facers and glass fiber reinforcement from recycled content (GAF, 2020). This recycled content is not expected to contribute additional hazardous content. EPS insulation appears to typically contain recycled content from its own manufacturing process, in which case it would not introduce any different chemicals to the product (EPS Industry Alliance, 2017). Some EPS products can contain up to 25-35% recycled content which is primarily pre-consumer (EPS Industry Alliance, n.d.; Insulation Corporation of America, n.d.; Insulfoam, 2016). The nature of the recycled content is not disclosed, but given that polystyrene typically makes up over 95% of the product weight, it is expected that this recycled content is polystyrene and likely EPS scrap from other facilities. XPS insulation may contain post-consumer recycled content (Kingspan Insulation, 2014; Owens Corning, 2019, 2020a). This may be EPS beads or densified EPS foam (Owens Corning, 2019). Less than 5% post-consumer polystyrene is reported in XPS products in Europe (EXIBA, 2019). It is unclear whether the pre-consumer recycled EPS foam or the post-consumer polystyrene used is from packaging, insulation, or another application. A closed-loop recycling process is under development in the EU that claims to be able to remove HBCD from EPS, allowing it to be recycled into insulation feedstock free of HBCD, but this project is still under development (PolyStyreneLoop Cooperative, n.d.). For existing recycled polystyrene feedstocks, if post-consumer EPS or XPS insulation is used, HBCD would be a concern and could lead to exposure for recycling workers and dispersion into the broader environment when the material is processed.

Plastic foam insulation materials almost always include blowing agents and flame retardants. Many of these are hazardous or have life cycle concerns due to their halogenated nature. Considering performance requirements early in the design process may allow selection of a plastic material that has safer alternatives available, such as a reactive, non-halogenated flame retardant.

Because the polymer is formed during the product manufacturing stage for polyiso, concerns about hazardous monomers are part of this life cycle stage. Similarly, SPF is still in its unreacted form, where hazardous monomers can be a concern. In contrast, polystyrene insulation is manufactured from the polymer. Residual monomers at much lower percentages in the product could be a concern during product manufacturing. Halogenated flame retardants are a concern across the board for plastic foam insulation, but non-halogenated options exist and are in use for some polyiso products. These are expected to be less of a concern.

Use

Installation

EPS, XPS, Polyiso

EPS, XPS, and polyiso insulation have few exposure concerns during installation. For some applications, adhesives may be used which could introduce additional hazardous chemicals, so mechanical installation is preferred when possible. Adhesives also make reclamation and reuse less plausible at the end of life (EXIBA, 2019). Cutting of foam board insulation is usually minimal, but could result in the generation of dust that could potentially expose installers to chemicals of concern or release them into the environment.

SPF

SPF insulation is delivered to the job site as two separate components and reacts during installation to form a foamed insulation. Most SPF insulation must be installed by professional applicators (SPFA, 2018) though some low pressure systems are available at home improvement retailers and may be purchased by individual consumers (Guo, Wong, Hanley, Gress and Schnell, 2017). Hazardous chemicals are given off during the installation process including isocyanates, whose respiratory impacts can come both from breathing in vapors and from skin contact with the chemicals (Guo et al., 2017; US EPA, 2015). Spills or leaks and cleaning processes present potential for additional exposure, as does the presence of unreacted isocyanates in dust created during trimming (Guo et al., 2017; US EPA, 2015). A U.S. review of unpublished industrial hygiene studies conducted between 2007 to 2014 indicated that SPF applicators and workers in close proximity to them are potentially exposed to levels of MDI in excess of occupational exposure limits such that personal protective equipment is required (Wood, 2017). Required PPE for spray foam installation usually includes full body protection in the form of disposable coveralls, chemical-resistant gloves and boots or booties, a hood, and eye and face protection as well as supplied air respirators (Sustainable Workplace Alliance, n.d.; O. US EPA, n.d.; Wood, 2017).

Building occupants should vacate a building during installation of spray foam insulation and until the foam has finished curing and the building has been ventilated and thoroughly cleaned. The EPA notes that, "It is not clear how much time is needed before it is safe for unprotected workers or building residents to re-enter. Re-entry time is dependent on product formulation and other factors that affect the foam curing rates" (US EPA, n.d.). Common industry practice is waiting 24 hours after completion of spray foam installation for re-entry (Wood, 2017).

While the industry has taken measures to provide educational materials and many installers most likely follow the prescribed guidelines, the fact remains that there are still cases where homeowners or installers become ill because of spray foam installation (Guo et al., 2017). Problems noted in the last several years by the Occupational Health Clinical Centers in New York include: "possible improper application of the foam; inadequate respiratory protection and ventilation for workers; spray foaming when the building was occupied; re-occupying too soon (estimated at 23-72 hours but there is little evidence to support current recommendations); and lack of warning about the health hazards of spray foam insulation for the home owners and workers." (Lax, Siwinski and Wigmore, 2016; Occupational Health Clinical Centers, 2016)

Use as Installed
Table 3 summarizes some of the primary differences between the product types being considered and likely exposure scenarios during product use as installed.

Table 3. Chemicals present in the product as installed. **Chemicals that are in red and bolded are identified as Substances of Very High Concern (SVHC) for REACH.** Chemicals in red and underlined are on the SIN list. *Substances in italics are chemicals identified by HBN as a high priority to avoid in insulation* that are not already highlighted in the SVHC or SIN list.

	EPS	XPS	Polyiso	SPF
Flame Retardant	**HBCD** Or *Benzene, ethenyl-, polymer with 1,3- butadiene, brominated*	**HBCD** Or *Benzene, ethenyl-, polymer with 1,3- butadiene, brominated*	TCPP Or Non-halogenated flame retardant - part of polyisocyanurate polymer	TCPP
Blowing Agent	Pentane Cyclopentane Isopentane	*HFC-134a* Or *HFO-1234ze* Or CO_2 and hydrocarbons such as isobutane	Pentane Occasional: 1-bromopropane	*HFC-245fa* (closed cell SPF) Water (open cell SPF)
Potential Residuals and Byproducts*	Styrene	N/A	N/A	Dibutyltin dilaurate *MDI* 1,4 dioxane 1,2-dichloropropane 1,2-dichlorobenzene
Optional Additives	Insecticide: such as Disodium octaborate tetrahydrate	N/A	N/A	N/A

Potential Exposure Scenarios	Direct human via product Human and environment via environmental releases from product	Direct human via product Human and environment via environmental releases from product	Direct human via product Human and environment via environmental releases from product	Direct human via product Human and environment via environmental releases from product

*Some studies have considered emissions from SPF insulation over time. Those chemicals identified in literature that are not already included as content or potential residuals in the table are listed as potential byproducts if they are SVHCs or on the SIN List.
Sources for table: (Healthy Building Network, n.d.; Naldzhiev, Mumovic and Strlic, 2020; Poppendieck, Gong and Lawson, 2016)

Flame retardants

As noted above, plastic foam insulation almost always contains flame retardants in order to meet flammability standards, but the type of flame retardant used can vary in ways that impact toxicity and potential for exposures. Flame retardants used in plastic insulation are commonly halogenated (containing either chlorine or bromine).

EPS and XPS manufacturers have historically used the flame retardant hexabromocyclododecane (HBCD), an SVHC. HBCD is considered a persistent organic pollutant (POP) under the Stockholm Convention. It was added to Annex A in 2013 along with a provision for a time-dependent exemption for HBCD used in EPS and XPS in buildings (UNEP, 2018). Consequently, China is able to use HBCD in EPS and XPS and produce it for this use until the end of 2021 (UNEP, n.d., n.d.). Numerous alternatives to HBCD have been identified, including non-halogenated alternatives, but not all have the same level of performance and some carry known health and environmental hazards (UNEP, 2012). Based on the information available, where manufacturers have phased out HBCD, they are typically using a brominated polymeric flame retardant that is reported to have the same flame retardant efficiency as HBCD (UNEP, 2012). The polymeric nature makes it less likely for the flame retardant to be emitted from the product and expose individuals during the product life. Additionally, its human health and ecotoxicity hazards are also predicted to be lower than for HBCD (USEPA, 2014).

SPF and polyiso insulation commonly use tris(2-chloroisopropyl) phosphate (TCPP) as a flame retardant. TCPP is an organophosphate flame retardant that has been identified in indoor air and dust (Dedeo and Drake, 2017). It is on the SIN List and ECHA has recommended TCPP for restriction in flexible polyurethane foams in childcare articles and residential upholstered furniture (ECHA, 2018).

Flame retardants like TCPP and HBCD are not chemically bonded to the insulation. Consequently, they can leach out of the product during use, creating potential for users to be exposed via dermal contact, inhalation, or ingestion of contaminated food, water, or dust (Babrauskas et al., 2012). Polymeric flame retardants, as larger chain chemicals, are less likely to migrate from products during use. Similarly, reactive flame retardants become part of the polymer chain during the manufacturing process and are also less likely to be emitted from a product during use and subsequently expose building occupants. Innovation has led to the availability of a reactive, non-halogenated flame retardant option that is currently used in some polyiso products and is advertised for use in polyurethane insulation (Symes and Leifer, 2017).

Resources are increasingly available to provide information on inherently safer alternative additives. For example, the ChemFORWARD platform includes flame retardants with full chemical hazard assessments that can be used in a diversity of materials ("ChemFORWARD," n.d.). The PINFA product selector is another resource for finding non-halogenated flame retardants by material compatibility and functional use ("Product Selector," n.d.).

Blowing agents

Blowing agents are another concern during product use. In North America, HFC blowing agents with high GWP are still used in XPS and SPF insulation. HFC-134a is commonly used in XPS and HFC-245fa is common in closed cell SPF. These blowing agents are expected to offgas from the product over its entire lifecycle, including during its use phase (Owens Corning, 2019). EPS and polyiso insulation, on the other hand, commonly use pentanes, which do not have a high global warming potential, as blowing agents.

Other emissions

Besides potential emissions of flame retardants and blowing agents during product use, a range of chemicals have been measured in emissions from various SPF products. A NIST report detected more than 80 different chemicals emitted from one SPF sample (Poppendieck et al., 2016). Some emissions may occur primarily during the month or less following installation. Others may continue over longer periods of time (Naldzhiev et al., 2020). Several chemicals identified in SPF emissions are on the SIN List. Installation conditions and the closed cell or open cell nature of the foam may impact the chemicals emitted and the rate of emission.

During the use phase as installed, EPS and XPS insulation made with the polymeric, brominated flame retardant and polyiso made with the reactive non-halogenated flame retardant are expected to be of lower hazard and less exposure potential than products that contain flame retardants like HBCD and TCPP. EPS is processed at a lower temperature than XPS, so is more likely to have residual styrene monomer. Emissions of residual hazardous chemicals are possible from SPF insulation and may vary depending on the on-site installation conditions.

End of Life

Most often plastic insulation is landfilled or incinerated at the end of the product's life. For example, in Europe, about 53% of EPS construction waste is incinerated for energy recovery, about 40% is landfilled or incinerated without energy recovery, and only 7.5% of EPS waste is recycled (PolyStyreneLoop Cooperative, n.d.). Because polyiso and SPF insulations are thermoset materials, they are inherently more challenging to recycle than thermoplastic materials, like polystyrene (ChemistryViews.org, 2019; Spray Polyurethane Foam Alliance, n.d.). This can be a consideration when choosing the polymeric material to use in design of an insulation product. New research programs, such as Europe's "PUReSmart," are also looking into ways to recover used polyurethane products and develop sorting technologies and chemical recycling to turn used polyurethane into raw materials for new products (ChemistryViews.org, 2019).

Hazardous additives make products more challenging to recycle into new products if those additives need to be removed to make the material a feasible recycled feedstock, and they can also impact options for material disposal. For example, management of waste containing HBCD is addressed under the Basel Convention (UNEP, 2015).

Landfill

Because plastic foam insulation is designed to last over 50 years, at the end of its life it can contain legacy chemicals that have since been phased out of new products. For example, most of the EPS and XPS in buildings currently contains HBCD (US EPA, 2020). Likewise, older formulations of XPS and SPF insulation may retain a small percentage of their CFC and HCFC blowing agents, which have both high GWP and high ODP. While options exist to collect and destroy these blowing agents (American Carbon Registry (ACR), 2017; US EPA, 2018), most foam insulation is likely to be landfilled, where the remaining blowing agent in the product can be released.

As with EPS and XPS, polyiso and SPF insulations are also most often landfilled (PIMA, 2015; SPFA, 2018). Consequently, disposal of each type of insulation has the potential to introduce HBCD or TCPP into the environment. Numerous leaching studies have presented pathways for potential exposure to HBCD from EPS and XPS (US EPA, 2020).

Recycling

No formal programs for recycling XPS insulation exist in the U.S. Likewise, in Europe landfilling and incineration are the most likely end of life options for XPS (EXIBA, 2019). There are formal programs in North America for post-consumer and post-industrial recycling of EPS materials, but this is primarily for EPS packing, and most EPS insulation is expected to be landfilled (EPS Industry Alliance, 2017).

One closed-loop recycling facility is under development in the Netherlands that will use a proprietary process to recycle XPS and EPS insulation, while removing the HBCD and recycling the bromine (EXIBA, 2020; PolyStyreneLoop Cooperative, n.d.). The U.S. EPA has determined that recycling of EPS and XPS panels containing HBCD presents a risk to aquatic organisms due to exposure to HBCD based on monitored and modeled surface water concentrations of HBCD (US EPA, 2020). Consequently, a closed-loop process that is able to recycle the bromine may have potential to mitigate some of this risk. The facility, however, will only have capacity to recycle 3,000 tons of EPS and XPS insulation annually, meaning most EPS and XPS insulation waste will not likely be recycled.

As noted above, polyiso and SPF are most often landfilled. In addition, because SPF insulation is foamed in place, it adheres to the materials around it and can be difficult to separate from these other building materials, potentially making it difficult to recycle otherwise recyclable materials.

HBCD in existing building insulation can also present an occupational risk during removal of EPS and XPS insulation. In 2020, a U.S. EPA risk evaluation determined that HBCD presents an unreasonable risk for six conditions of use including during removal and recycling of EPS and XPS foam panels. The report determined that demolition teams are at risk for thyroid hormone disruption affecting offspring and developmental toxicity due to acute and chronic inhalation exposure (US EPA, 2020).

Policy Considerations

Regional regulations and voluntary industry programs can influence how products are made across the world. Because of HBCD's status as a persistent organic pollutant (POP) and regulation of the use of high-GWP blowing agents, many insulation manufacturers have shifted to chemicals that are considered less harmful to human health and the environment. Although there is a global trend to move away from these chemicals, a large degree of regional variability still exists. This section highlights examples of policies that impact regional variability.

Regulations

HBCD was added to Annex A of the Stockholm Convention in 2013. Although it is considered a POP under the Convention, countries could apply for an exemption on the use of HBCD in EPS and XPS in buildings given that articles containing HBCD are easily identifiable throughout their lifecycle (UNEP, 2018). Currently, only China and South Korea have active exemptions which gave them an additional five-year period to transition away from the use of HBCD in EPS and XPS, although both exemptions are set to expire soon (UNEP, n.d.). In accordance with the Stockholm Convention, regions have taken action to restrict and prohibit the use of HBCD in all sectors. For instance, HBCD was sunset in the EU in 2015, so it is no longer added as a flame retardant in insulation (ECHA, n.d.). Although India has not updated its National Implementation Plan since 2011, in 2018 the government passed legislation prohibiting the manufacture, trade, use, import, and export of seven POPs including HBCD (Ministry of Environment, Forest and Climate Change, 2018). Although the U.S. is not a signatory of the Stockholm Convention, as a result of global restrictions on HBCD they have phased away from its use as well. Industry representatives there indicate that there has been no domestic manufacture of HBCD since 2018, and use of stockpiles and exportation was completed in 2017 (US EPA, 2020).

California has new legislation allowing polystyrene insulation without flame retardants to be used below grade beneath cement slabs (Charbonnet et al., 2020; Melton, 2019). Products for this application are exempted from meeting the open flame standard that plastic foam insulation must typically meet (Charbonnet et al., 2020). Polystyrene insulation used elsewhere in a building still will require the addition of a flame retardant to meet the open flame testing standard. Other regions have building codes that consider assembly-level fire performance as opposed to an open flame test of the bare insulation. As a result, for example, flame retardant-free polystyrene boards dominate the market in Scandinavia (Charbonnet et al., 2020).

The Montreal Protocol has driven the transition from CFCs and HCFCs to HFCs in many sectors, including insulation, given that the latter have no ozone-depletion potential. They do, however, have high GWP. To address this, the Montreal Protocol was amended in 2016. Under the Kigali amendment, countries are required to phase down the use of HFCs at different rates that will drastically cut HFC emissions by the middle of the century (UNTC, 2016).

Alternative blowing agents for XPS, such as hydrofluoroolefins (HFOs), have begun to emerge in markets like the EU (JACKON Insulation GmbH, 2015). These HFOs have low global warming potential but they can be manufactured with chemicals that have high global warming potential, as noted in the Product Manufacture section. XPS using non-halogenated blowing agents including carbon dioxide is also available in Europe (EXIBA, 2019). In the U.S., EPA regulations that would have prohibited the use of HFCs in XPS insulation by 2021 have been overturned by the courts. Several states in the U.S. have moved forward with their own regulations based on the previous EPA timeline, but the industry association is fighting these regulations, citing concerns over potential supply chain issues resulting from inconsistencies in requirements in different states (Garry, 2019; Taylor, 2020).

<u>Industry Programs</u>
Very few options exist to recycle EPS and XPS insulation. The PSLoop Project noted above, headed by a non-profit based in the Netherlands, began in 2017 and will conclude in 2023 and is designed to create a facility that can recycle 3000 tons of EPS and XPS construction waste each year (PolyStyreneLoop Cooperative, n.d.).

Individual manufacturers have also taken measures to reduce the use of high-GWP blowing agents in product formulations. For instance, Owens Corning announced that they will begin using a reduced global warming potential blowing agent in a new line of XPS insulation beginning in 2021. The blowing agent is proprietary, but the manufacturer claims that it will reduce GWP by 90%, presumably relative to the HFC blowing agents used in its current XPS formulations (Owens Corning, 2020b).

<u>Additional Policy Considerations</u>
Unlike some other construction materials, there do not appear to be significant take-back programs for plastic insulation materials. Applying extended manufacturer responsibility requirements to insulation materials is one potential policy consideration to increase collection, reuse, and recycling of plastic insulation.

Another policy lever that could impact the sustainability and toxicity of plastic foam insulation materials is the consideration of building code requirements that lead to the inclusion of flame retardants in insulation. Alternative fire safety methods such as thermal barriers have been demonstrated to protect thermal insulation better than flame retardants in the insulation (Charbonnet et al., 2020).

Conclusion

In this insulation case study we explored how the selection of base plastics and associated chemical additives impacts the exposures to hazardous chemicals for fenceline communities, building occupants, and workers during manufacturing, installation, use, and end of life. We also discussed how these materials and additives impact the ability of those materials to contribute to a circular economy. Trade-offs exist at each stage of the product's life-cycle between EPS, XPS, polyiso, and SPF plastic insulation. Below is a summary of important criteria to consider when designing plastic insulation to reduce the impacts on human health and the environment. These criteria broadly include considerations from OECD Policy Principles for Sustainable Materials Management: 1) Preserve natural capital; 2) Design and manage materials, products, and processes for safety and sustainability from a life-cycle perspective; and 3) Use the full diversity of policy instruments to stimulate and reinforce sustainable economic, environmental, and social outcomes.

1. **Chemical Hazards of Base Polymer and Source Materials**: Consider chemical hazards in the supply chain for the base polymers under consideration. Choose a plastic type based on inherently

safer chemistry and look for safer process chemistry options within a plastic type when they exist. Prioritize avoidance of hazardous chemicals where there is greatest potential for exposure.

2. **Chemical Hazards of Additives/Additive Life Cycle**: Consider the chemical hazard of additives and potential impacts on workers, building occupants, and the broader environment. When data is available, consider life cycle impacts for the manufacture of additives. Particularly because of the long life cycle of building insulation, consider potential future regulations and emerging chemicals of concern. Key additive considerations for plastic foam insulation include:
    a. **Flame Retardants**: Avoid using halogenated flame retardants, if alternatives are available that meet performance requirements and have been assessed for their hazard properties to ensure they are less hazardous.
    b. **Blowing Agents**: Avoid the use of halogenated blowing agents when alternatives can meet performance requirements. Consider other changes to the product content or manufacturing process that can maintain or increase product performance while using alternative blowing agents.
3. **Chemical Hazards During Use**: Consider where in the life cycle chemical reactions take place and design products where reactions take place in controlled environments to reduce potential exposures. Avoid designing products that react on site where there is less control.
4. **Options for Recycled Feedstocks without Hazardous Content**: Consider options for recycled feedstocks. Prefer recycled feedstocks that are from known sources and tested for common hazardous content to avoid introducing hazardous content into new products.
5. **Recyclability and Availability of Recycling Infrastructure**: Consider whether the material is recyclable at end of life and if a recycling infrastructure exists or is under development. Design for recyclability becomes meaningful only when it is practically implementable. Prefer plastics that are recyclable and have effective collection and recycling infrastructure in place, or partner with others to develop this infrastructure as part of the product development process. Increased reclamation and recycling of materials when a building is renovated or demolished is needed in general. Efforts that generate content transparency about products can aid in understanding of product content at this stage and increase potential for effective recycling.

Application of Criteria to Case Study

1. **Chemical Hazards of Base Polymer and Source Materials.** Polystyrene and polyurethane/polyisocyanurate chemistry both require the use of hazardous chemicals. Polystyrene chemistry does not appear to require the use of SVHCs. It also does not require the use of isocyanates, which are potent respiratory sensitizers. It does, however, require the use of benzene and styrene, which are both on the SIN List. Between these two chemistries, polystyrene has less hazardous chemicals in the base polymer manufacturing. There are options for some different chemical pathways for polyurethane/polyisocyanurate manufacturing; if opting for these types of polymers, prefer processes that minimize the use of SVHCs. Other polymer options may allow further reduction in chemical hazards during the manufacturing process. Product manufacturers can compare all options to better understand the impacts and choose the best polymer for their product.

2. **Chemical Hazards of Additives/Additive Life Cycle**
    a. **Flame Retardants.** All product types considered commonly contain halogenated flame retardants. Within currently available plastic foam products, halogen-free polyiso avoids halogenated flame retardants. Based on the information publicly available, the alternative appears to be of lower hazard.
    b. **Blowing Agents.** Closed cell SPF and XPS insulation commonly use halogenated blowing agents. EPS, open cell SPF, and polyiso avoid the use of halogenated blowing agents. XPS insulation without halogenated blowing agents is available in some regions, but does see a decrease in insulative performance as a result of the blowing agents used.
3. **Chemical Hazard During Use.** Both closed-cell and open-cell SPF react on site as installed and can expose installers to isocyanates, which are respiratory sensitizers. Even with proper PPE there is an increased risk of exposure to harmful chemicals during installation than for other types of plastic foam insulation.
4. **Options for Recycled Feedstocks without Hazardous Content.** Some EPS and XPS insulation contains pre-consumer recycled content, and some XPS insulation may contain small quantities of post-consumer recycled content. If post-consumer recycled content from insulation is used, it should be ensured that legacy hazardous chemicals like HBCD are not present or have been removed.
5. **Recyclability and Availability of Recycling Infrastructure.** Minimal reclamation or recycling of plastic foam insulation seems to be taking place currently. Innovation is needed in this sector both from a product design perspective and a recycling perspective. Product manufacturers should design products with a circular economy in mind, by avoiding chemical additives that reduce the value or recyclability of the product. Manufacturers can also participate in and support materials transparency, materials tracing, and engage with recyclers. For example, manufacturers can participate in initiatives like EPS Industry Alliance efforts to collect and recycle EPS packaging and the PSLoop project to recycle EPS and XPS and remove HBCD. In addition, policies supporting extended manufacturer responsibility programs or building code adjustments could be implemented.

This case study focuses on comparing plastic insulation materials; however, additional insulation materials are available including fiberglass, mineral wool, cork, and cellulose. Healthy Building Network has generated an Insulation Hazard Spectrum that places these products on a continuum of improvement based on the goal of hazard avoidance. Product types at the green end of the spectrum typically have lower human health and environmental concerns than those in the yellow or orange colors, while those at the red end of the spectrum should be avoided when possible (See Appendix B). In product design, innovation may require the consideration of vastly different materials versus making incremental improvements in chemistry for a particular type of product.

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Appendix A. Product Composition

A Common Product profile is a list of substances that are most commonly present in a product type as delivered to building sites. The profiles are not specific to any manufacturer. Although Common Products are specific to product compositions in North America, for this report we highlight potential regional variations that may exist outside of this region.

XPS Insulation (Extruded Polystyrene) Common Product*

Chemical	CASRN	% Weight Product	Function
Polystyrene	9003-53-6	88.3%	Base Resin
HFC-134A	811-97-2	6.2%	Blowing Agent
Methyl Formate	107-31-3	2.2%	Blowing Agent
Polymeric Brominated Flame Retardant	1195978-93-8	1.7%	Flame Retardant
Pentane	109-66-0	0.9%	Blowing Agent
Talc	14807-96-6	0.3%	Nucleating Agent
Pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate)	6683-19-8	0.2%	Stabilizer
Epichlorohydrin, O-cresol, Formaldehyde Polymer	29690-82-2	0.1%	Stabilizer
Calcium Stearate	1592-23-0	0.09%	Lubricant
3,9-Bis(2,4-di-tert-butylphenoxy)-2,4,8,10-tetraoxa-3,9-diphosphaspiro(5.5)undecane	26741-53-7	0.02%	Stabilizer

*For a full list of sources used to generate this Common Product see Pharos. "XPS Insulation (extruded polystyrene)." Accessed September 18, 2020. https://pharosproject.net/common-products/2078867. Common Product research methodology is described in detail at https://pharosproject.net/common-products/methodology.

EPS Insulation (Expanded PolyStyrene) Common Product

To be added: https://pharosproject.net/common-products/2079007

Polyisocyanurate Wall Insulation Board Common Product

To be added: https://pharosproject.net/common-products/2085579

Spray Foam Insulation Common Product

To be added: https://pharosproject.net/common-products/2079008

Appendix B. Healthy Building Network Insulation Hazard Spectrum

Hazard spectrums organize Healthy Building Network's research, identifying practical attributes to look for when specifying safer products, and red-flagging products or chemicals to be avoided. Individual products can vary significantly in their health and environmental profiles; however, some types are generally better than others when it comes to the health of building occupants, installers, and the broader environment. HBN uses a simplified spectrum to rank different types of products within a product category. You can use it to benchmark your current practice and take a step up to healthier options. Products in green categories are typically the best options, whereas products at the bottom of the spectrum, in red, are to be avoided. Those in between provide intermediate options from a health hazard perspective.

The Insulation Hazard Spectrum encompasses a wide variety of insulation options, including fiberglass, mineral wool, cellulose, and plastic foam insulation.

- Expanded Cork
- Blown-In Fiberglass (Loose Fill, Dense Pack, and Spray-Applied)
- Kraft-Faced and Unfaced Fiberglass Batts
- Formaldehyde-Free Mineral Wool Batts
- Halogen-Free Polyisocyanurate
- Unfaced Cellulose/Cotton Batts
- Blown-In Cellulose (Loose Fill, Dense Pack, and Wet-Blown)
- PSK or FSK-Faced Fiberglass Batts or Blankets
- Mineral Wool Batts and Boards
- Fiberglass Board (Duct Insulation)
- Expanded Polystyrene (EPS)
- Polyisocyanurate (Polyiso)
- Traditional Expanded Polystyrene (EPS)
- Extruded Polystyrene (XPS)
- Traditional Extruded Polystyrene (XPS)
- Spray Polyurethane Foam (SPF)